Modeling Arabian Dust Mobilization During the Asian Summer Monsoon: the Effect of Prescribed Versus Calculated SST

R. L. Miller,[1,2] J. Perlwitz,[1,2] and I. Tegen[3,4]

Emission of soil (or 'mineral') dust aerosol over the Arabian Peninsula during the Northern Hemisphere (NH) summer monsoon increases in response to dust radiative forcing in an atmospheric general circulation model (AGCM) with prescribed sea surface temperature (SST). Radiative heating within the dust layer reinforces the monsoon circulation, which is further strengthened by column latent heating through a wind-evaporative feedback. The strengthened circulation raises additional dust into the atmosphere over Arabia. In contrast, this positive feedback is absent when SST is calculated by the AGCM using a mixed-layer ocean. This discrepency results from the surface energy constraint in the mixed-layer experiment, where surface evaporation is decreased by the reduction of sunlight beneath the dust layer. In contrast, evaporation and column latent heating increase in the prescribed SST experiment, where the surface energy constraint is absent. Realization of the positive feedback exhibited by the prescribed SST experiment requires that anomalous ocean heat transport (which is not included here) balance the surface radiative forcing by dust.

1. Introduction

Soil (or 'mineral') dust aerosol influences climate through mechanisms ranging from fertilization of ocean biogeochemical cycles [*Bishop et al.*, 2002] and mediation of atmospheric chemistry [*Dentener et al.*, 1996; *Trochkine et al.*, 2003] to direct radiative forcing [*Andreae*, 1995]. Changes to the atmospheric circulation by dust radiative forcing have been calculated by numerous studies [*Coakley and Cess*, 1985; *Miller and Tegen*, 1998]. Because lifting (or 'emission') of dust into the atmosphere is closely related to the surface wind, circulation changes driven by dust feed back upon the aerosol load. In the current climate, this feedback is negative, reducing the global emission of dust by roughly 15%, according to two AGCM experiments that include dust as a tracer [*Perlwitz et al.*, 2001; *Miller et al.*, 2004a]. The two AGCMs are identical except for their lower boundary condition: SST is prescribed by *Perlwitz et al.* [2001] using the climatological seasonal cycle, whereas *Miller et al.* [2004a]

[1]Department of Applied Physics and Applied Math, Columbia University, New York, New York, USA.
[2]NASA Goddard Institute for Space Studies, New York, New York, USA.
[3]Max Planck Institute for Biogeochemistry, Jena, Germany.
[4]Institute for Tropospheric Research, Leipzig, Germany.

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allow SST to adjust to dust radiative forcing by using a mixed-layer ocean model. For both models, the reduction in emission is similar for all source regions, with the exception of Arabia during the Asian summer monsoon. In the mixed layer experiment, Arabian emission is reduced during NH summer (JJA), indicating a negative feedback (Figure 1a). However, for prescribed SST, dust radiative forcing actually increases JJA emission by over 50% in one experiment (denoted by '0.9ϖ' in Figure 1b). In this case, the feedback between radiative forcing and emission is positive.

In this article, we attribute the contrasting feedbacks to the lower boundary condition adopted by each AGCM. The presence of a surface energy budget only in the mixed layer experiment results in a contrasting surface wind response to the reduction of sunlight beneath the dust layer. The effect of the surface energy budget upon the temperature and precipitation response to dust has been noted by *Miller and Tegen* [1998]. Here we show that the feedback of dust radiative forcing upon emission depends upon the inclusion of this budget.

2. Model Description

In both AGCM's, dust emission, transport, and deposition are calculated as a function of the evolving model climate [*Tegen and Miller*, 1998]. Radiative forcing of the climate by dust, and the associated feedback upon the dust cycle, was included by *Perlwitz et al.* [2001] and *Miller et al.* [2004a]. The effect of dust radiative forcing upon emission during the NH summer monsoon is calculated by contrasting the dust cycle in AGCM experiments that include and omit this forcing. Dust optical properties for all source regions are taken from laboratory measurements of Saharan dust collected over the Atlantic [*Volz*, 1973; *Patterson et al.*, 1977]. The resulting global average single scatter albedo, which depends upon the contribution of each particle size category, is 0.906 [*Miller et al.*, 2004b]. Because of global variations in aerosol mineralogy [*Sokolik et al.*, 1993] along with uncertainty in Saharan dust properties [*Sinyuk et al.*, 2003], two additional experiments with dust radiative forcing are carried out where the particle single scatter albedo is either decreased (corresponding to increased absorption) or increased (corresponding to increased reflection) by 10%. In the latter case, the single scatter albedo is not allowed to exceed unity. For brevity, we present only the experiments with enhanced absorption (denoted by '0.9ϖ' in Figure 1), because the effect of the lower boundary condition upon JJA emission is most apparent. According to Figure 1, the emission contrast is smaller for more reflecting particles (denoted by '1.1ϖ') and intermediate for Saharan particles (denoted by '1.0ϖ'). In the conclusions, we discuss the relevance of the experiments with enhanced absorption.

For the experiments with prescribed SST, physical quantities shown below represent climatological averages over 26 years of model output. Results from the mixed layer experiments represent averages over the final 31 years of integration, following a 19 year period when the model comes into equilibrium with the dust radiative forcing. As a result of the long averaging period for each experiment, the differences we discuss in the text are distinct from internal model variability at the 95% confidence level at minimum.

3. Results

Figures 2a and b show the anomalous dust load during NH summer in the vicinity of the western Indian Ocean, downwind of Arabian and East African sources. For each lower boundary condition, the JJA anomaly is constructed from the difference between the experiments with and without dust radiative forcing. This difference represents the response to dust radiative forcing, except for radiative fluxes, where the difference also includes the forcing.

In the mixed-layer experiment, dust radiative forcing reduces the aerosol load almost everywhere. *Miller et al.* [2004a] show that the decrease of sunlight beneath the dust layer reduces the surface flux of sensible heat back into the atmosphere. This weakens mixing within the planetary boundary layer, with a consequent reduction in momentum transport to the surface, the surface wind speed, and dust emission. Despite this effect, the dust load is strongly increased downwind of the Arabian peninsula when SST is prescribed (Figure 2a).

Figures 2c and d show the anomalous wind speed. The unperturbed monsoon circulation consists of easterly flow along the equator, turning to southerly flow along the east African coast and southwesterly flow across the Arabian Sea and Indian subcontinent toward the Bay of Bengal (Figure 3). In the experiment with prescribed SST, the increased dust load is associated with a strengthening of the surface winds across the southern Arabian peninsula. In addition, the wind anomaly augments the southwesterly monsoonal flow along the Arabian coast.

We interpret the strengthened monsoon circulation in the prescribed SST experiment as the result of anomalous column diabatic heating (Figure 2e). This heating consists of column radiative heating, the surface sensible heat flux, and latent heat release within ascending air. Radiative heating within the dust layer (Figure 4a) represents an elevated heat source. This strengthens the monsoon southwesterlies along the Arabian coast, increasing the surface latent heat flux (Figure 4c), equal to evaporation times the latent heat of vaporization. The associated latent heat release (Figure 4e) further strengthens the monsoon circulation, including the surface winds across the southern Arabian peninsula.

In contrast, the anomalous diabatic heating is much smaller in the mixed-layer experiment (Figure 2f). This contrast is almost entirely due to the comparatively small anomaly of column latent heating in the mixed-layer experiment (Figure 4f). This results from the negative anomaly of the surface latent heat flux along the Arabian coast (Figure 4d). In the absence of a column latent heating anomaly, the circulation change is comparatively modest (Figure 2d).

Ultimately, the contrasting feedback resulting from the two boundary conditions can be traced to the surface energy budget. Neglecting heat storage by the ocean, the reduction of sunlight beneath the dust layer must be balanced in the mixed-layer experiment by a reduction in heat transfer from the surface back to the atmosphere. The surface latent heat flux is reduced (Figure 4d), despite the increase in wind speed, and the net surface heat flux is nearly zero (Figure 5b). In contrast, a surface energy constraint is absent in the prescribed SST experiment. Despite the reduction of incident sunlight by dust, the ocean gives up additional heat to the atmosphere (Figure 5a) through the anomalous surface latent heat flux that results from the increased surface wind speed.

4. Conclusions

In the prescribed SST experiment, dust radiative forcing enhances the NH summer monsoon circulation, increasing evaporation along the Arabian coast. This leads to additional diabatic heating by latent heat release, further intensifying the monsoon circulation. The strengthened circulation raises additional dust over Arabia. In contrast, evaporation decreases in the mixed layer experiment, in response to the reduction of sunlight beneath the dust layer. In the absence of a column latent heating anomaly that would augment radiative heating within the dust layer, the change in the monsoon circulation and Arabian dust emission is negligible.

It remains to be shown whether the observed monsoon circulation is reinforced by radiative forcing from Arabian dust. This feedback should depend upon the geographic distribution of Arabian dust aerosol: the positive feedback exhibited with prescribed SST is absent in an AGCM with a different distribution of dust (Martin Werner, personal communication, 2004).

The contrasting feedback that results from the two lower boundary conditions is most apparent for the absorbing particle experiment (0.9ϖ in Figure 1), where the column radiative heating is largest. In contrast, the feedback is nearly identical between the two boundary conditions for reflecting aerosols. Aerosol optical properties derived from Saharan dust result in an intermediate contrast. Optical measurements of Arabian dust indicate slightly greater absorption at solar wavelengths than the Saharan value used here [*Ackerman and Cox*, 1988].

Black carbon (BC), an aerosol exhibiting greater solar absorption than dust, is abundant over the Indian subcontinent [*Ramanathan et al.*, 2001]. The anomalous column latent heating in response to BC radiative forcing is geographically similar to the anomaly in Figure 4e associated with a strengthened monsoon circulation and increased Arabian dust emission [*Wang*, 2004].

The mixed layer experiments preclude any feedback by ocean currents. The positive feedback between dust radiative heating and emission in the prescribed SST experiment may be realized if ocean currents supply the heat lost by enhanced evaporation and the aerosol forcing. During the NH summer, the ocean is observed to gain heat through the surface along the Arabian coast [*Weller et al.*, 1998]. In the prescribed SST experiment, dust reduces the surface heat gain by roughly one-half. A consideration of ocean dynamics must be included to determine whether the positive feedback upon emission can be realized.

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R. L. Miller, Dept. of Applied Physics and Applied Math, Columbia University, 2880 Broadway, New York, NY 10025. (rlm15@columbia.edu).

J. Perlwitz, Dept. of Applied Physics and Applied Math, Columbia University, 2880 Broadway, New York, NY 10025. (jp544@columbia.edu).

I. Tegen, Institute for Tropospheric Research, Permoserstr. 15, 04318, Leipzig, Germany. (itegen@tropos.de)

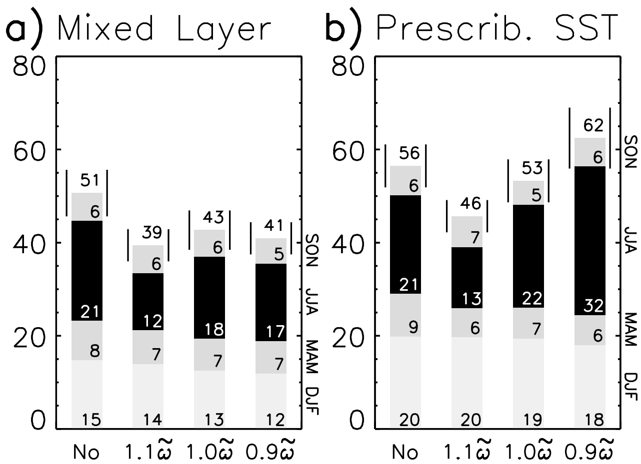

Figure 1. Emission of soil dust aerosol (Tg) over Arabia, as calculated by each experiment. (Arabia is defined east of the Red Sea between 35–60°E and 12–36°N.) The experiment omitting dust radiative forcing is denoted by 'No', while the experiments including forcing are denoted by 1.0ϖ, 0.9ϖ, and 1.1ϖ for baseline, more absorbing, and more reflecting particles, respectively. The annual average is listed at the top of each bar, with black shading marking the JJA contribution. The vertical lines bracketing the annual average represent the 95% confidence interval of the uncertainty. Note the increasing contrast of JJA emission between the mixed-layer and prescribed SST experiments as particle absorption increases.

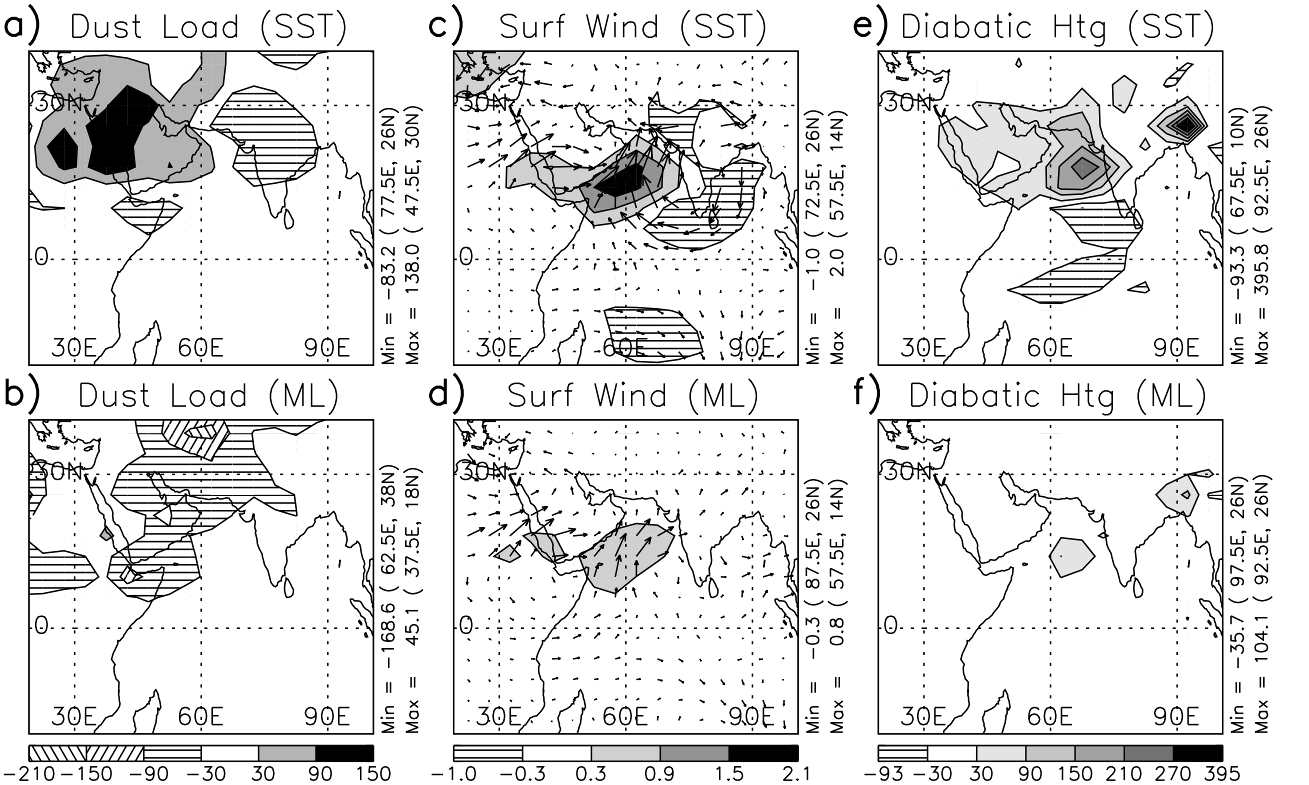

Figure 2. Anomalous dust load ($\mathrm{mg\,m^{-2}}$), surface wind speed ($\mathrm{m\,s^{-1}}$), and column diabatic heating ($\mathrm{W\,m^{-2}}$) during NH summer for more absorbing particles, given (top) prescribed SST and (bottom) a mixed-layer ocean.

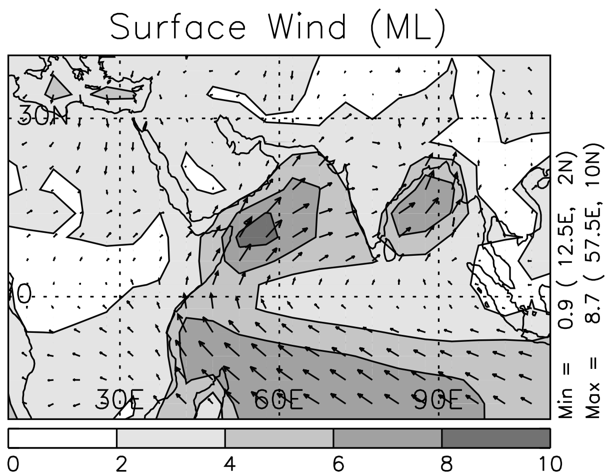

Figure 3. Climatological surface wind speed ($\mathrm{m\,s^{-1}}$) and direction during NH summer for the mixed-layer experiment without dust radiative forcing.

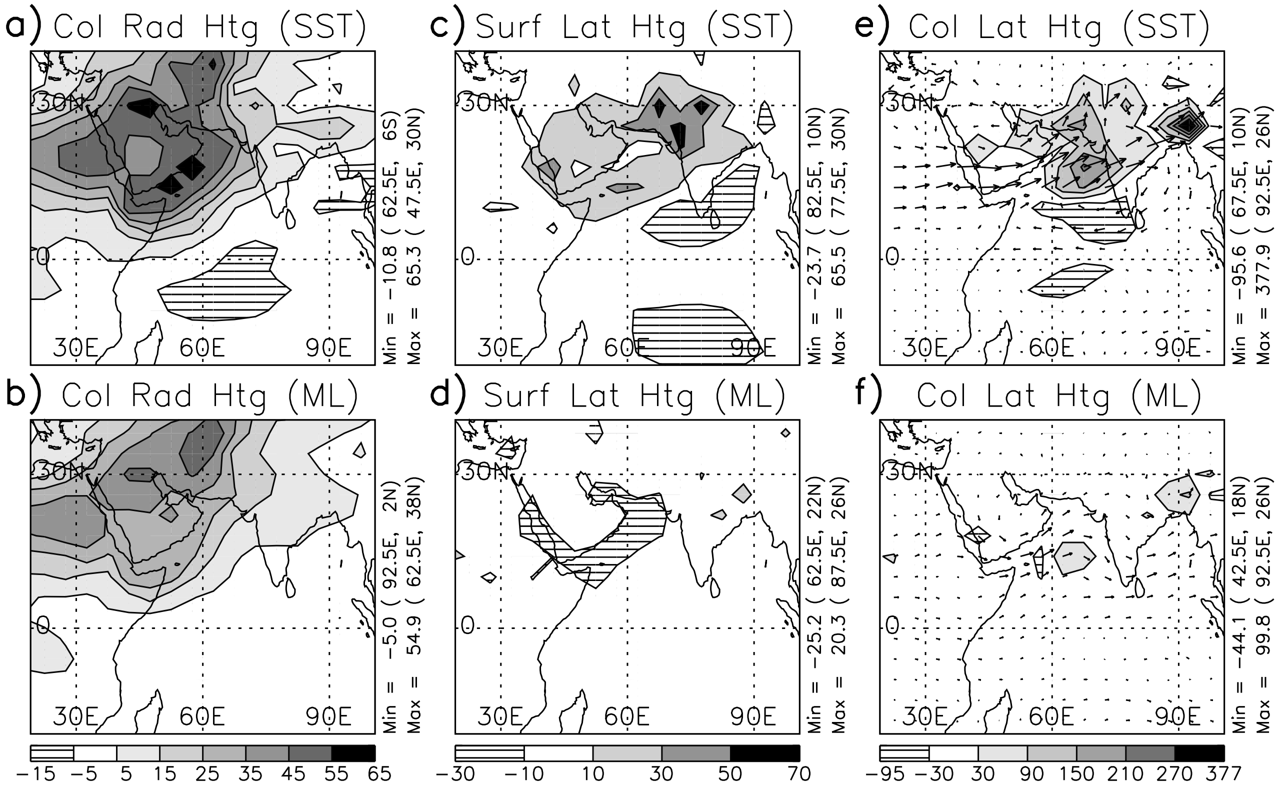

Figure 4. As in Figure 2 but for JJA anomalies of column radiative heating, the surface latent heat flux, and column latent heating (along with the column-integrated moisture flux), all in $\mathrm{W\,m^{-2}}$.

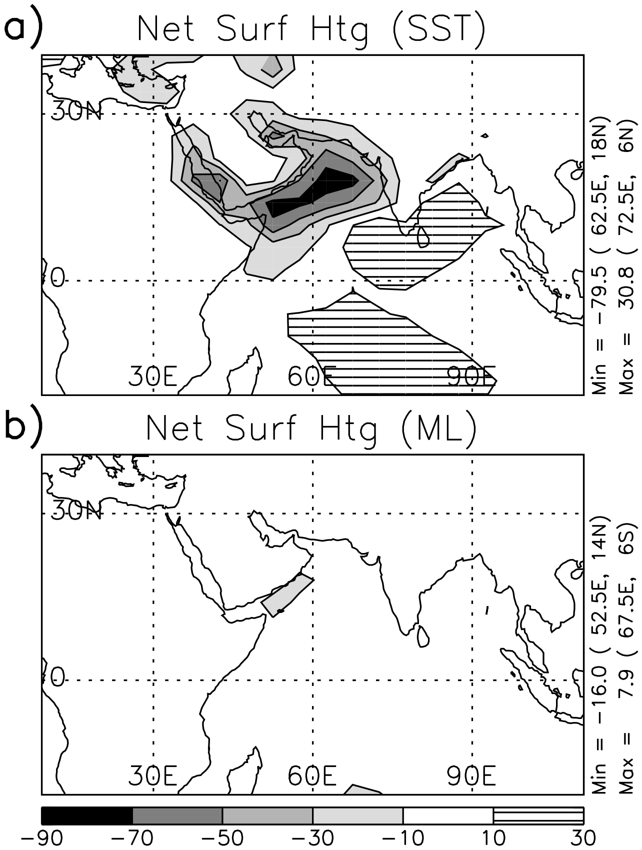

Figure 5. As in Figure 2 but for JJA anomalies of the net surface heat flux into the ocean ($\mathrm{W\,m^{-2}}$).